Registration for computer-navigated surgery in edentulous patients: A problem-based decision concept

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Abstract: BACKGROUND: Surgical navigation is a commonly used tool in cranio-maxillofacial surgery. Registration is the key element for precision, and a number of studies have shown different techniques to be accurate. Nonetheless, uncertainty surrounds the special situation in edentulous patients and a practical approach to what can be a challenging problem. MATERIALS AND METHODS: Four registration strategies for the Brainlab VectorVision(2) system are presented for surgical navigation of edentulous patients: three landmark-based, point-to-point techniques and one surface-based matching strategy are evaluated. RESULTS: The methods described differ in overall accuracy as well as in the region covered. In general, the more time-consuming and invasive the technique, the more precise it is. The non-invasive techniques are less precise, and they cover only small regions with sufficient accuracy. CONCLUSIONS: Taking into account which type of accuracy is clinically relevant and that the whole skull does not always need to be covered with the greatest possible accuracy, all the described techniques have their indications. The simpler and less invasive techniques can spare time, decrease costs, and harm patient. A decision tree is presented to the reader.

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ABSTRACT

Background

Surgical navigation is a common tool in cranio-maxillofacial surgery. Registration is the key element for precision, and a number of studies have shown different techniques to be accurate. Nonetheless, uncertainty surrounds the special situation of edentulous patients and a practical approach to their sometimes challenging problem.

Materials and methods

Four registration strategies for the Brainlab VectorVision^2 system are presented for surgical navigation of edentulous patients: Three landmark-based, point-to-point techniques and one surface-based matching strategy are evaluated.

Results

The described methods differ in overall accuracy as well as in the covered region. In general, the more time-consuming and invasive the technique, the more precise it is. The non-invasive techniques are less precise, and they cover only small regions with sufficient accuracy.

Conclusions

Taking into account which type of accuracy is clinically relevant and that the whole skull does not always need to be covered with the greatest possible accuracy, all the described techniques have their indications. The simpler and less invasive techniques can spare time, costs, and patient harm. A decision tree is presented to the reader.

Keywords

Computer-navigated surgery; maxillofacial surgery; craniofacial surgery, cone beam computer tomography; registration

INTRODUCTION

Surgical navigation plays an increasingly important role in modern cranio-maxillofacial surgery (*Gellrich et al.,* 2002; *Schmelzeisen et al.,* 2002; *Schmelzeisen et al.,* 2004). Baseline three-dimensional (3D) data is derived mostly from computer tomography (CT), magnetic resonance tomography (MRI), or—nowadays more and more—from cone beam computer tomography (CBCT) (*Eggers et al.,* 2009).

Most of the appliances and studies focus on the mid-face region, especially the orbit with its complex anatomy (*Watzinger et al.,* 1997; *Marmulla and Niederdellmann,* 1998; *Gellrich et al.,* 2002; *Schmelzeisen et al.,* 2004; *Feichtinger et al.,* 2007; *Kokemueller et al.,* 2008). Even the fronto-orbital and skull base regions have been addressed (*Hassfeld et al.,* 1998; *Schmelzeisen et al.,* 2002; *Fei et al.,* 2007). The literature deems the situation for navigation in the mandibular area as unsatisfactory (*Siessegger et al.,* 2001), partly because of lack of experience with navigation of the mandible.

Correct registration is the key element to accurate surgical navigation (*Eggers et al.,* 2006) because has direct repercussions on the precision of all subsequent navigation tasks (*Luebbers et al.,* 2008). Insecurity, however, still surrounds registration strategy. Most studies focus on the possible achievable accuracy of one or more registration techniques. Few focus on the differences in accuracy that depend on the navigated region and its distance from the region used for registration (*Luebbers et al.,* 2008). As a consequence, concepts for different clinical situations are missing.

In this study different concepts of registration are evaluated for their clinical aspects. They can be divided into the two subsets, marker-based (*Altobelli et al.,* 1993; *Hassfeld et al.,* 1995; *Howard et al.,* 1995; *Schramm et al.,* 1999) and marker-free procedures (*Troitzsch et al.,* 2003; *Marmulla et al.,* 2004b; *Hoffmann et al.,* 2005;

Marmulla et al., 2005b), which do not need any artificial landmarks. The marker-based registration techniques described to date employ bone-implanted screws (*Sinikovic et al.,* 2007), fiducials fixed to a dental splint (*Schramm et al.,* 2001), or reference markers glued to the skin (*Alp et al.,* 1998; *Hardy et al.,* 2006).

The marker-free techniques rely on the patients' anatomy and either register against defined bone areas, such as the Anterior Nasal Spine (*Swennen et al.,* 2006), or they register through extraction of the skin surface out of the 3D dataset, matching it with a laser scan of the patient's skin (*Grevers et al.,* 2002; *Hoffmann et al.,* 2005; *Marmulla et al.,* 2005a).

Each technique has advantages and disadvantages in matters of precision (*van den Elsen et al.,* 1982; *Maciunas et al.,* 1994), covered field of acceptable precision (*Luebbers et al.,* 2008), and, of course, harm to the patient when it comes to such invasive techniques as bone-anchored fiducials (*Sinikovic et al.,* 2007).

The aim of this study was to evolve a protocol that provides a registration concept that is applicable for typical situations in edentulous patients.

METHOD

Using the Brainlab VectorVision[2] system (Brainlab AG, Heimstetten, Germany) four different registration concepts are described and evaluated. Accuracy measurements were performed utilizing unharmed bone structures in various regions that were exposed due to surgical access as e.g. orbital wall, frontal or parietal skull or any regions of the midface and the maxilla.

<u>Implanted bone screws serving as fiducials</u>

Implanted bone screws can serve as fiducials for the point-to-point registration technique. In most cases the screws are purposely inserted to serve as fiducials. In these cases we do place the screws under local anesthesia and through aesthetically uncritical approaches into regions that are spread over a wide anatomical field (Figure 1).

Occasionally osteosynthesis material has already been inserted due to prior surgery. This is the case, for example, in secondary correction of insufficiently treated midface trauma (Figure 2).

Laser surface scanning

In laser surface scanning, a so called z-touch laser scans the surface of the periorbital region. The computer matches the scan against the soft tissue surface derived out of a 3D dataset acquired by MSCT, CBCT, or MRI. Soft tissue situations—for example, swelling—have to be excluded for laser surface scanning procedures, or they must be addressed by a very short time period between the scan and the surgical procedure.

Fiducials fixed to prosthesis

Since the classical registration technique used by cranio-maxillofacial surgeons—the point-to-point technique employing fiducials positioned in a splint mounted to the upper jaw, as described by Schramm et al. (*Schramm et al.,* 1999; *Schramm et al.,* 2001)—is not applicable in edentulous patients, we modified this technique into fixating the fiducials directly to the prosthesis as shown in Figure 3.

Anatomical landmarks

Most navigation systems do offer the option of referencing through anatomical landmarks. These have to be identified in the dataset at the planning computer during the planning process or intraoperatively at the navigation system itself.

RESULTS

Implanted bone screws serving as fiducials

If bone screws are used for point-to-point registration, a 3D dataset needs to be acquired after insertion of the screws. This might mean an additional radiological examination for the patient, which has to be justified. The bone screws can easily be positioned under local anesthesia. We did use regions of preexistent scarring or expected surgical approaches as well as aesthetically preferable regions, either intraoral or in the area of the haired skull. Due to geometric considerations the polygon spanned by the screws should be as large as possible to achieve a big field of maximum accuracy (Figure 1). Taking this into account, the precision and the size of the covered field are extraordinarily good compared to every other technique.

Mostly the achieved accuracy is below 1mm. We did not experience inaccuracies above 1.5mm in any region of any patient.

<u>Laser surface scanning</u>

Use of laser surface scanning for registration does not need additional datasets if one has already been acquired and if the soft tissue status—e.g., in matters of swelling or larger body mass changes—is not an issue. We did experience some difficulties in adjusting the correct threshold for a good match. This problem seems to be more of an issue with CBCT datasets than with others. However, we could achieve a match in all cases.

Once registered successfully, the covered field is almost as big as it is with the bone-anchored screws. However, the clinical accuracy seems to be lower and—even more important—less predictable. Any intraoperative soft tissue manipulation may prevent necessary re-registration.

We experienced situations were no matching at all was possible as well as cases with accuracy around 1mm. Mainly we achieved accuracy levels around 2mm.

<u>Fiducials fixed to prosthesis</u>

Using fiducials for point-to-point registration requires that a 3D dataset be acquired after fixation of the fiducials to the prosthesis (Figure 3). The procedure might mean an additional radiological examination for the patient, which has to be justified.

With a stable and reproducible position of the prosthesis, we did get accuracy levels within the range of occlusal splints (Figure 4). Due to geometric considerations the polygon spanned by the screws should again be as big as possible to achieve a reasonable field for good accuracy.

The field of acceptable accuracy is smaller than with bone-anchored screws or laser surface match.

Mainly the achieved accuracy in the midface and orbital floor region was between 1 and 2mm. It decreased down to 5mm e.g. in the region of the frontal skull. However, if position of prosthesis is poorly defined inaccuracies of about 5mm can occur in any region.

Anatomical landmarks

If anatomical landmarks are used for point-to-point registration, additional datasets are not needed if one has already been acquired.

Under clinical circumstances we did not obtain sufficient results for registration via anatomical landmarks. The identification of anatomical landmarks is quite simple in general, but the precise location of each landmark is difficult to judge in CT as well as in the surgical site. For both intra- and inter-observers, reproducibility is an issue.

We especially experienced problems in defining an exact location of a landmark within the 3D dataset. Often there were not enough clearly defined landmarks within the prospective field of surgery, and we did not accept the necessity to expose bone structures only for registration reasons when splint registration or laser surface matching was an alternative.

Our experiences with anatomic landmarks only for referencing purposes were mainly frustrating with inaccuracies of 3 to 5mm.

DISCUSSION

Implanted bone screws serving as fiducials

In previous studies the concept of widely spread bone-anchored fiducials and, based on those, a point-to-point registration has shown excellent results for overall accuracy and the covered field (*Maciunas et al.,* 1993; *Luebbers et al.,* 2008). But the clear down side of this technique, of course, is the necessity to implant the screws and to acquire a new 3D dataset afterward. This issue does not apply in cases with osteosynthesis material that has been integrated into the patient in a prior surgery (*Maciunas et al.,* 1992; *Marmulla et al.,* 1997b; *Schramm et al.,* 2007).

Laser surface scanning

The same study by Luebbers et al. did reveal comparably good results for laser surface scanning technique (*Luebbers et al.,* 2008). These have to be interpreted very carefully because the study design excluded the influence of soft tissue movements, and those are supposed to have the biggest impact on precision of surface matching techniques. However, our clinical experiences as well as the numerous studies do suggest acceptable accuracy for laser surface matching (*Marmulla et al.,* 1997a; *Raabe et al.,* 2002; *Schlaier et al.,* 2002; *Marmulla et al.,* 2003; *Troitzsch et al.,* 2003; *Marmulla et al.,* 2004a; *Marmulla et al.,* 2004b; *Marmulla et al.,* 2004c; *Hoffmann et al.,* 2005; *Marmulla et al.,* 2005a). This technique very often does not need additional 3D imaging for surgical navigation and has no need of preoperative invasive procedures in order to prepare the patient for the computer-assisted surgery. Soft tissue swelling in posttraumatic situations can be a contraindication for surface registration. The sometimes necessary re-registration due to inaccuracies that develop within longer surgeries also is not possible if, e.g., a coronal approach was performed or other factors influenced the soft tissues during surgery.

Fiducials fixed to prosthesis

To avoid the harm of screw implantation by keeping the advantages of fix reference points including the possibility of re-registration Schramm et al. developed the concept of an occlusal splint which is the basis for our concept of screw fixation to the patient's prosthesis. One downsize of both techniques is that studies showed a direct link between accuracy of a region and distance from the reference center (*Schramm et al.,* 2007; *Luebbers et al.,* 2008). However, the midface up to and including the orbital floor is covered; therefore, this technique is indicated in many situations.

Regarding re-registration procedures the surgeon must be aware that any approach compromising the mucosa under the prosthesis might prevent re-registration. However, most indications for surgical navigation can be approached without mobilization of the fixed mucosa of the hard palate and the alveolar ridge.

Anatomical landmarks

We clearly do not recommend the use of anatomical landmarks, due to our experiences, the known inaccuracies, and the observed dependency on a precise location, all of which result in poor registration (*Yau et al.,* 2005; *Hardy et al.,* 2006; *Yau et al.,* 2007; *Lubbers et al.,* 2010a).

Despite these limitations anatomical landmarks as an additional feature to either surface registration or prosthesis / splint based registration might raise the achieved precision and in particular widen the area of high precision through the larger volume encompassed by the reference polygon (*Schramm et al.,* 2007).

Alternative techniques

All presented techniques of course can be varied and - at least partially – be combined.

Bone screws can be placed intraorally only (*Schramm et al.,* 2007). This avoids scarring for the prize of a smaller reference polygon and therefore smaller region of high accuracy (*Schramm et al.,* 2007; *Luebbers et al.,* 2008).

Screw fixation to the prosthesis can be spared and an occlusal or vestibular splint can be attached to the prosthesis similar to the technique in patients with sufficient dentition (*Schramm et al.,* 1999). Inaccuracies occuring due to the splint-prosthesis-interface should be small compared to the problem of prosthesis position itself. Advantages are the unharmed prosthesis, the possibility of archiving the splint for later use and last not least upper and lower prosthesis can both be included into the referencing splint. This expands the polygon and therefore widens the field of precision. Position of the two-prosthesis-construction might be more reliable compared to a single prosthesis and additionally the lower jaw is positioned and therefore also available to surgical navigation(*Lubbers et al.,* 2010b).

The possibility of intraoperative 3D imaging nowadays does lead to another option of registration without the need of fiducials at all. An intraoperative dataset can simply be matched onto the preoperative one which includes the surgical plan. In situations without extensive pre-planning the intraoperative dataset can be the only one excluding the disadvantage of an additional dataset.

Regarding the number of reference points Schramm et al. demonstrated a reduced accuracy if more than 4 fiducials are utilized. But this effect is smaller as e.g. the influence of the size of the volume encompassed by the fiducials on a maxillary splint (*Schramm et al.,* 2007). Under clinical circumstances we didn't see the effect of too many fiducials at all. This might be due its small influence or due to the fact that modern navigation systems automatically discard reference points that calculate imprecise compared to the others if redundant numbers are utilized. E.g. in laser surface matching up to 10% of all surface points are discarded. However, we prefer to have at least 5 reference points (with a navigation system that requires a minimum of 4) in case one gets lost for whatever reason.

The weakness of the study obviously lies in the lack of statistical analysis for accuracy measurements. But a concept which allows sufficient statistical analysis of this data is in our eyes almost impossible since e.g. in each patient there are differences in the bone regions that can be evaluated. Further than that each registration process is different due to e.g. swelling of the soft tissues or stability of the prosthesis. After all we believe that this weakness is overcome by the realistic daily clinical setting presented in combination with the long evaluation period and therefore high number of cases performed.

Based on the points discussed above, a decision tree for the registration of edentulous patients can be developed as shown in Figure 5. Depending on different clinical factors, this decision tree should suggest the correct registration concept. It is, of course, important to check the registration against landmarks meticulously, no matter which strategy has been chosen. In our clinic we do perform landmark checks before any navigational checking period within surgery and additionally whenever any doubt arises—e.g., after unintended contact with the dynamic reference fixed to the skull.

With impending new software developments, combinations of registration techniques will be introduced, such as point-to-point registration combined with laser-scan technology. These new techniques will have to be evaluated under experimental and clinical circumstances, and the decision tree will need to be adapted.

CONCLUSIONS

Depending on the needs of the surgical team in matters of accuracy and the field of surgical navigation covered, the surgeon should adjust the concept of registration applied. If this is done, additional surgical procedures, such as implantation of fiducials, can be spared, and also additional 3D imaging may be spared. Such procedures will lead to both time and cost reduction as well as to making patients more comfortable during the planning phase.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

CAPTIONS

Figure 1 Purposely inserted bone screws serving as fiducials for point-to-point registration in surgical navigation (Screws distributed over a wide area to achieve high accuracy over the whole skull and midface)

Figure 2 Osteosynthesis material due to prior insufficient reduction serving as fiducials (Screws) for point-to-point registration in surgical navigation (Utilized screws are distributed over a wide area)

Figure 3 Titanium screws serving as fiducials mounted to the patient's maxillary prosthesis. (Screw positioned with their heads to encompass a large volume)

Figure 4 Landmark check against unaffected orbital wall region after point-to-point registration with prosthesis-mounted fiducials (Figure 3) reveals high level of accuracy at the region of the medial orbital floor

Figure 5 Decision tree for registration concept in edentulous patient depending on required level of accuracy, prospective region of surgical navigation, and status of the patients prosthesis

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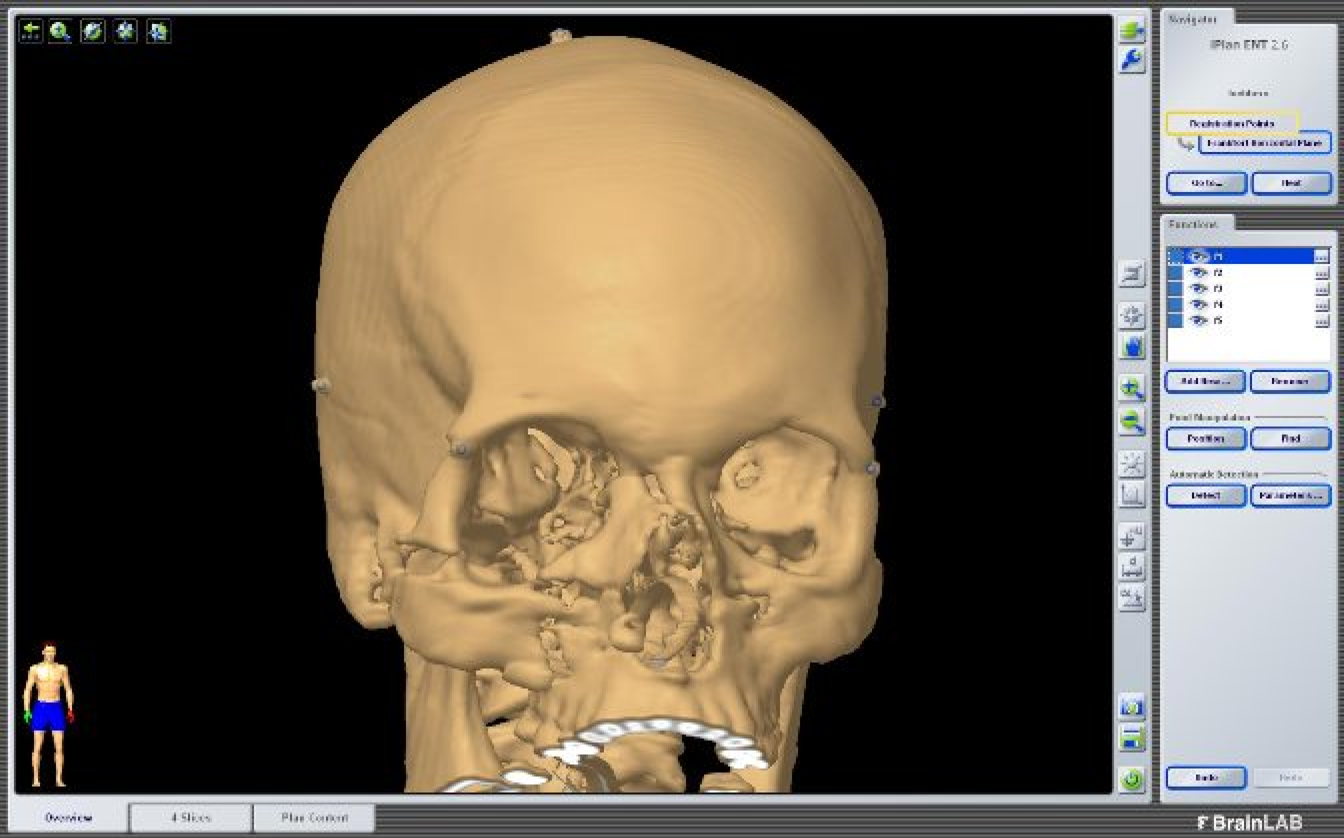
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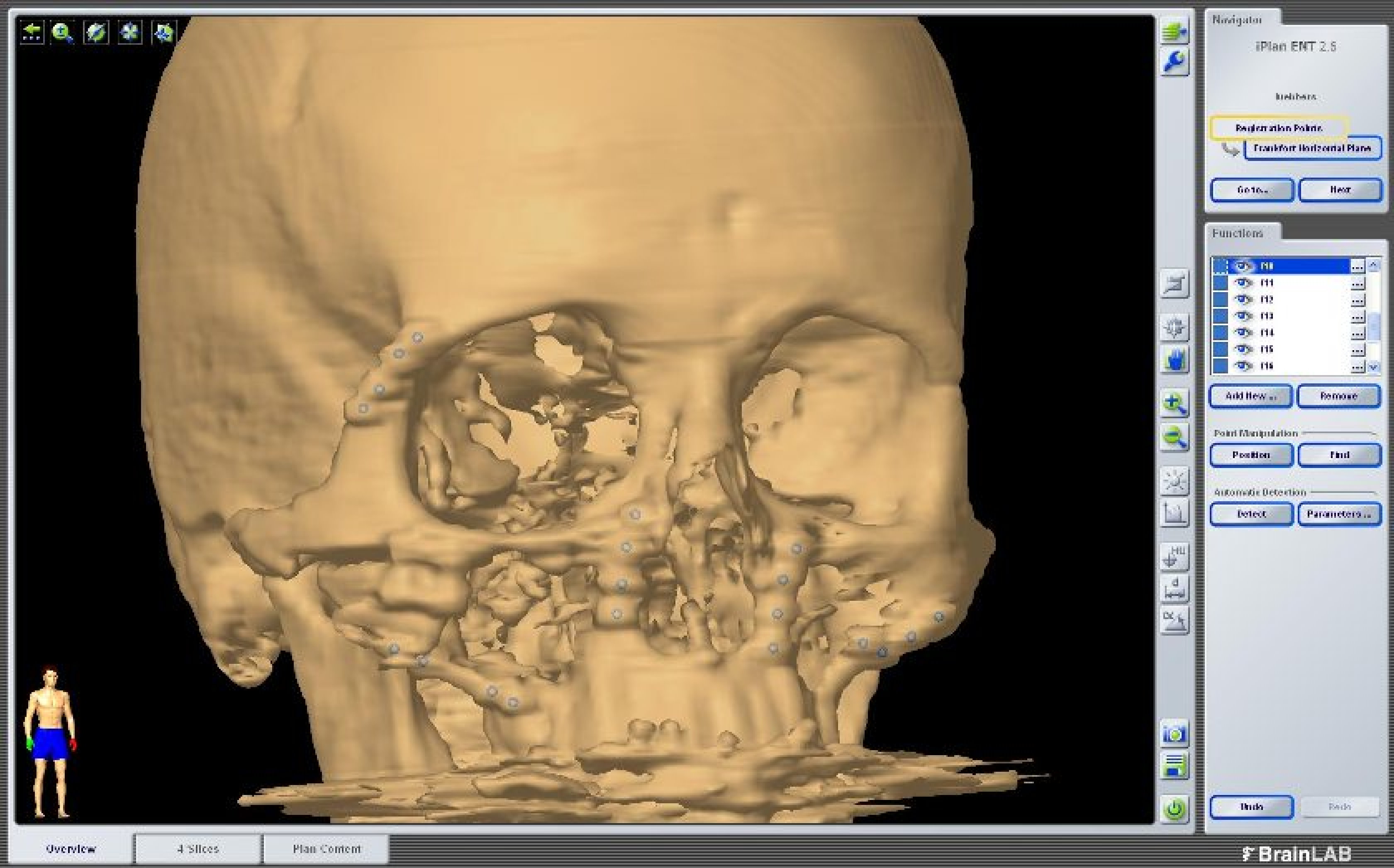
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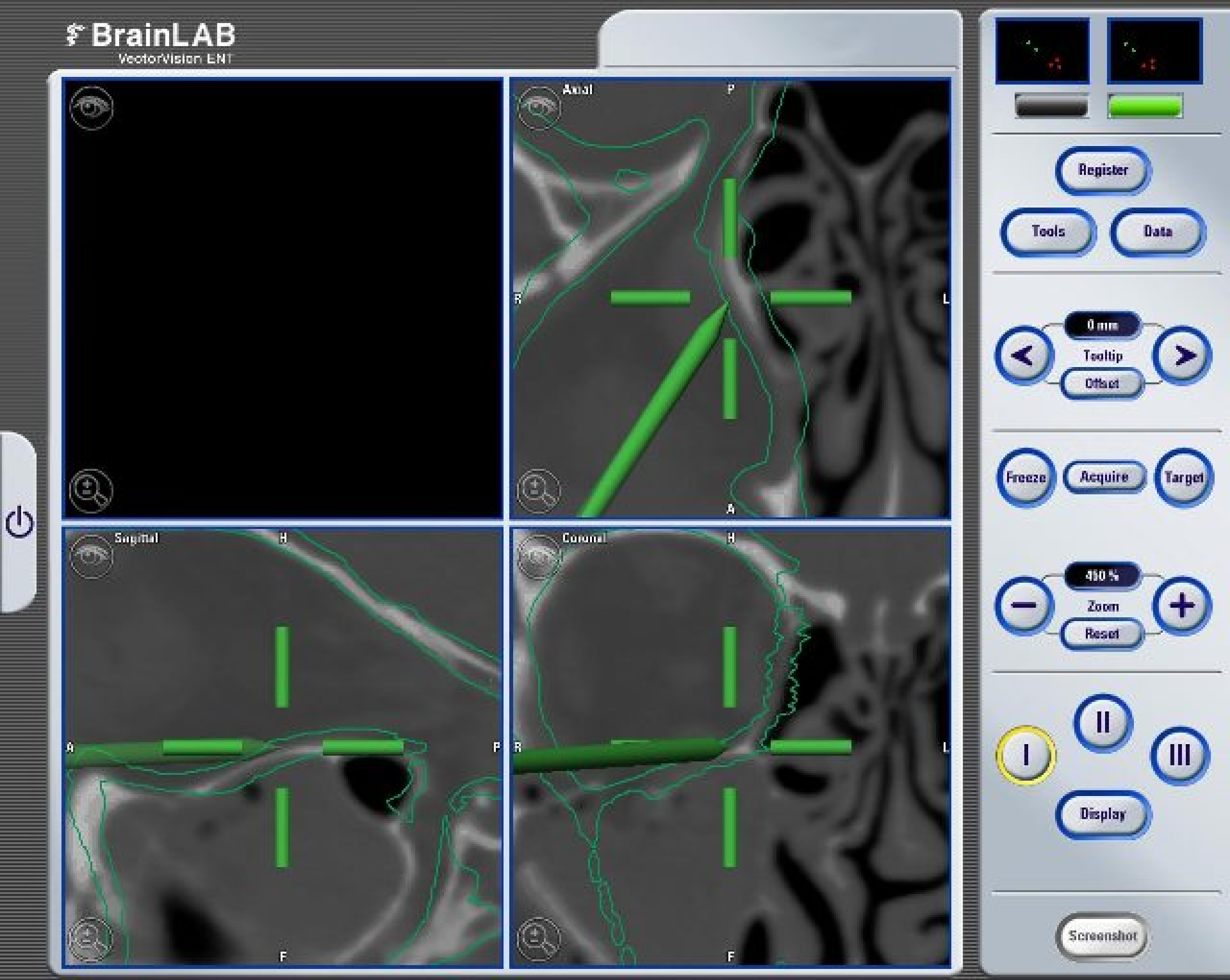
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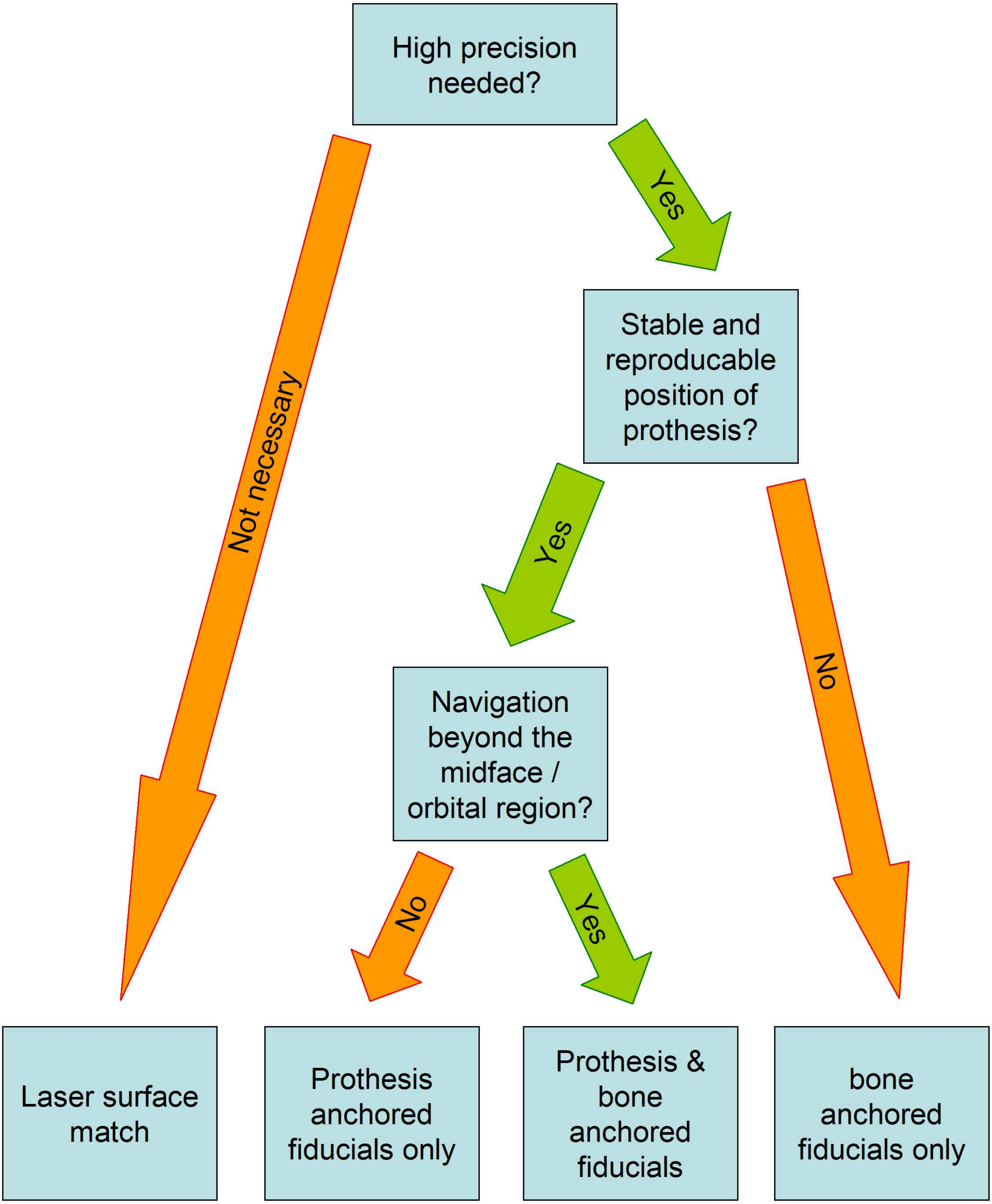
High precision needed?
Yes
Not necessary
Stable and reproducable position of prothesis?
Yes
No
Navigation beyond the midface / orbital region?
No
Yes
Laser surface match
Prothesis anchored fiducials only
Prothesis & bone anchored fiducials
bone anchored fiducials only